Laser cooling of stored relativistic C^{3+} ions at the ESR

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After several years of planning [1], development [2], and tests [3], in August 2012 a new laser cooling experiment (E089) has been performed at the ESR. One essential goal of this beamtime was to demonstrate that the initially 'hot' ions can be collected inside the rf-bucket using just the laser, *i.e.* without changing the bucket frequency and without electron cooling. This scheme can namely be used to cool relativistic ion beams in future storage rings and synchrotrons, such as the HESR and SIS-100 at FAIR. A second goal was to demonstrate *in vacuo* optical detection of the UV-light (ca. 155 nm) emitted from the laser excited ions. Finally, we wanted to perform a systematic study of several relevant parameters [4]. This also required collecting data from many different recently installed ESR diagnostic systems, such as the resonant Schottky pick-up [5], the ionization profile monitor [6], and UV-photochanneltrons [3].

Laser cooling of relativistic ions in a storage ring can be performed using only one anti-collinear laser beam and a bunched ion beam. We wanted to demonstrate two cooling schemes: In the first scheme, the CW laser frequency is rapidly scanned over a large range, cooling all ions inside the bucket. The group of Th. Walther at the TU Darmstadt has therefore developed a fast scanning narrowband CW laser system, based on a seeded fiber amplifier (1028 nm) with two frequency doubling stages (514 and 257 nm) [7]. In the second scheme, a powerful pulsed laser system (broadband) is used to cool many velocity classes in one shot. Here, a sufficiently high repetition rate is important, since the laser pulses must hit the ion bunches, which have a revolution frequency of about 1 MHz, often enough. Such a laser system, based on a fs-oscillator, a fiber-coupled diodelaser, an Yb:YAG amplifier medium (1028 nm), and two frequency doubling stages to reach 257 nm, has been developed by the group of U. Schramm from HZDR in Dresden [8].

As in the two previous ESR laser cooling experiments (2004 and 2006), we have used $^{12}C^{3+}$ ions[1] with $2s \rightarrow 2p$ cooling transitions and a kinetic energy of 122 MeV/u. Typically, about 10^8 ions were stored in the ESR for about 5 minutes. During the 8 days of beamtime, we were able to have a fully functional laser cooling setup. From the Schottky spectrum in figure 1 it can *e.g.* be seen that the CW laser slows down the ions (*i.e.* they obtain a lower frequency) as it is scanning through its range. Fluorescence from the laser excited ions has been recorded with the UV-photochanneltron detectors, made possible by the support from the group of G. Birkl at the TU Darmstadt. We have also observed that the laser cooling scheme can change the velocity of the stored carbon ions, even when electron cooling is trying to keep the ions at a fixed velocity. This clearly demonstrates the power of the method. Detailed analysis of the large amount of data is currently being carried out by the collaboration.

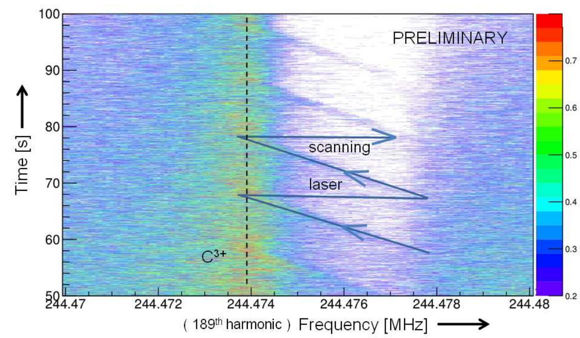

Figure 1: Schottky spectrum (time vs. frequency) of a stored C^{3+} beam in the ESR. The electron cooler is off, the ion beam is not bunched, and the CW laser scans through 12 GHz in 10 s. (All lines drawn are to guide the eye.)

In parallel to studies at the ESR, similar studies will be started at the CSRe storage ring in Lanzhou, China. The group of X. Ma in Lanzhou has also intensively contributed to the success of the recent ESR beamtime. The laser and detector systems will soon be shipped to Lanzhou.

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[1]With ca. 10% of $^{16}O^{4+}$ contamination from the ECR ion source.

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